NASA TECHNICAL NOTE

NASA TN D-2653

c. 1

NASA TN D-2653

AN EXPERIMENTAL INVESTIGATION OF PEAK AND AVERAGE HEATING EFFECTS IN CASCADE-ARC JETS

by W. D. Beasley, R. L. Barger, and J. D. Brooks

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1965

AN EXPERIMENTAL INVESTIGATION
OF PEAK AND AVERAGE HEATING EFFECTS
IN CASCADE-ARC JETS

By W. D. Beasley, R. L. Barger,
and J. D. Brooks

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $1.00

AN EXPERIMENTAL INVESTIGATION

OF PEAK AND AVERAGE HEATING EFFECTS

IN CASCADE-ARC JETS

By W. D. Beasley, R. L. Barger,
and J. D. Brooks
Langley Research Center

SUMMARY

The results of a systematic investigation of some gas heating characteristics of a supersonic arc jet are presented. The gas heating mechanism was a constricted arc in the throat of a cascade nozzle arrangement. The effects of varying the arc current, pressure, and flow medium on the ejection velocity and settling-chamber pressure rise were measured.

To the extent that the ejection velocity can be related to the peak throat temperature and the settling-chamber pressure to the average throat temperature, the results are consistent with experimental and analytical studies of stationary arcs.

INTRODUCTION

Research on electric arc heating of gas flow systems has been directed toward a number of aerospace applications including materials testing, aerodynamic testing, and electric rocket propulsion. One approach that has been studied especially in connection with electric rocket research is the use of a constricted arc confined within the nozzle throat as reported in reference 1.

Recently, the NASA Ames Research Center has reported (ref. 2) extremely high enthalpies obtained with a special type of supersonic jet that utilizes a constricted arc similar to the cascade arc used in Germany for studies of stationary arcs without flow as described in reference 3.

The present investigation of the gas heating characteristics of a cascade-arc-jet configuration is based on measurements of stream velocity and settling-chamber pressure. Velocities were measured directly by the method described in reference 4.

When analyzed in conjunction with the settling-chamber pressure rise data and with independent measurements and analytical results reported by other investigators, these velocity measurements give a consistent description of some of the characteristic properties of the arc and of the flow.

SYMBOLS

$\bar{j}$	average current density, total current divided by throat area, amp/cm^2
l/d	throat length-to-diameter ratio
$\dot{m}$	mass flow rate, g/sec
p	settling-chamber pressure, mm Hg
p_o	initial settling-chamber pressure, mm Hg
T	absolute temperature, $^{\circ}$K
V	velocity, m/sec

APPARATUS AND PROCEDURE

System Design

The flow system, schematically illustrated in figure 1, was somewhat similar to the arrangement employed in the investigation reported in reference 4. Three conical cascade-arc-jet nozzle configurations with different throat lengths were used in the present study. The short-throat and long-throat nozzles are shown schematically in figure 2. An intermediate-length-throat nozzle (l/d = 5:1) was also used. It differed from the long-throat nozzle (l/d = 9:1) in that one less cascade section, consisting of one copper disk and one boron nitride disk, was used in the constant-area section of the throat. Each nozzle had a throat diameter of 2.54 millimeters and a total included expansion angle of 60°. The cascade arrangement consisted of water-cooled copper disks separated from each other by thin boron nitride disks to provide electrical insulation in the axial direction along the arc column within the throat.

This cascade-arc-jet arrangement was somewhat similar to the configuration used in reference 2 but was smaller in throat diameter and length; also, in this investigation, the average arc current densities were higher and the mass flow rates smaller.

The cathode was an uncooled thoriated tungsten rod with a pointed tip. It was mounted on the center line of the nozzle and electrically insulated with a sleeve of boron nitride. Cathode diameters ranged from 1.6 millimeters to 4.8 millimeters with the choice of diameter appropriate to the range of current in the arc.

A copper disk at the nozzle exit served as the anode. The arc was confined between the cathode in the settling chamber and the anode in the low-pressure supersonic section of the nozzle so that it passed entirely through the throat. The cascade copper disks were water cooled from a high-pressure water supply manifold, and dielectric hoses were used to insure that each copper disk would be electrically insulated from the others.

The expansion chamber was equipped with a quartz window for observing the flow. The chamber, vacuum equipment, and instrumentation are described in detail in reference 4.

The usual operating flow medium was nitrogen; however, some measurements were made with argon so that the effects of current density in a monatomic gas and in a molecular gas could be compared. The d-c arc power for current up to 100 amperes was furnished by a 100-kilowatt machine with a constant-current output. Motor-generator welding machines were connected in series for current in excess of 100 amperes.

Measurements

The inlet gas volume flow was measured with a flowmeter, and the mass flow rate was determined from a calibration of the flowmeter for the gas pressure and temperature. The mass-flow-rate measurements were checked with a calibrated sonic orifice, and they agreed within 0.5 percent. Over the current range the mass flow rate was held constant within ±10 percent.

The settling-chamber pressure was measured with an aneroid-type absolute pressure gage. This gage has a range from 0 to 1,550 mm Hg.

Direct velocity measurements were made by creating a luminous disturbance in the flow and measuring its time of flight over a known distance with photomultiplier detectors. The method is described in reference 4. A small capacitor (0.03 microfarad) charged to a high d-c potential (usually 2,500 volts) is discharged into the low-impedance arc column and thereby produces a change in the ionization level of the arc. The result is a change in luminosity that persists in the flow for some time. Since the arc is confined in the throat, there is an appreciable radial temperature gradient and a consequent radial variation in the exit velocity. The measurement spark discharges through the path of least resistance; this path is along the hottest part of the arc column, which is considered to be along the arc axis or center line. Thus, the luminous disturbance detected in flight by the photomultiplier detectors was carried by the fastest part of the stream, and consequently the velocities measured were a maximum over the cross section of the flow.

RESULTS AND DISCUSSION

Measurements

Figure 3 presents data obtained with the short-throat nozzle with nitrogen plasma as the flow medium at $\dot{m} = 0.101$ g/sec. Both the peak (or center-line) velocity and the ratio of settling-chamber pressure with the arc in the throat to settling-chamber pressure before the arc was struck, p/p_o, are plotted against the average current density $\bar{j}$. Figures 4 and 5 show similar data for the intermediate- and long-throat nozzles, respectively, for several values of $\dot{m}$. Figure 6 presents data obtained with the long-throat nozzle with argon plasma as the flow medium.

Several points should be noted regarding the physical interpretation of the velocity and pressure measurements. The ejection velocity is a multiple of the sound speed in the throat. The sound speed has a complicated dependence on the following interrelated quantities: throat temperature, compressibility, and degree of ionization and dissociation. Ionization and dissociation both tend to increase the sound speed and consequently the ejection velocity.

Thus, to calculate accurately the throat temperature from the measured ejection velocity would be difficult. Nevertheless, some conclusions concerning the variation of the throat temperature may be drawn from the velocity measurements since the velocity increases when the temperature is increased and vice versa. As previously mentioned, the velocity measurement is related to the hottest part of the arc which is considered to be the arc axis or center line.

The settling-chamber pressure rise, p/p_o, is an approximate indication of the average heating of the gas passing through the nozzle throat. Under certain restricted conditions the total enthalpy of the flow can be calculated from the pressure rise by the well-known "sonic-flow" method (ref. 5). The calculation has not been made herein primarily because of the considerable radial temperature gradient that normally exists in this type of arc-flow arrangement. Also, the sonic-flow theory in its conventional form is not applicable when the flow is heated in the throat rather than in the settling chamber (ref. 5). Other complicating factors are the addition of some energy downstream of the throat minimum and the growth of boundary layer in the throat, which has been shown important in systems that utilize long-duct throats even at very high Reynolds numbers (ref. 6). Therefore, the settling-chamber pressure rise is used directly as an indication of the average gas heating.

Properties of the Plasma in Nozzle Throat

Throat length-to-diameter ratio.- In spite of the complications mentioned previously, certain conclusions regarding the properties of the plasma in the nozzle throat may be drawn from the velocity and pressure data. For the nozzles used, the settling-chamber pressure rise and the peak velocity increased with increasing length-to-diameter ratio. Comparison of figures 3, 4(b), and 5(b) reveals that, at roughly corresponding values of $\dot{m}$, both V and p/p_o

are lower for the short-throat nozzle than for the other nozzles at any given value of $\bar{j}$. This fact demonstrates that the temperature is lower in the short-throat nozzle - a result which is consistent with the discussion in reference 2 and also with the theoretical considerations of reference 7, which indicates that some length of arc traversal is required for the plasma to approach the conditions that exist in an arc without flow.

Effects of average current density.- Figures 4(a), 4(b), 5(a), and 5(b) show that as long as the settling-chamber pressure with the arc on $\left(p = p_o \frac{p}{p_o}\right)$ does not significantly exceed 1 atmosphere, the measured velocity initially rises rapidly with increasing $\bar{j}$ and then tends to level off until $\bar{j}$ attains a value of about 1,200 or 1,300 amp/cm^2, whereas the pressure rise is virtually linear over the range of $\bar{j}$. Thus, the peak throat temperature appears to increase sharply at low values of $\bar{j}$ and more gradually at high values, whereas the average temperature increases steadily.

These effects are consistent with the results of actual spectroscopic measurements made in a constricted cascade arc without flow and shown in figure 7. This figure summarizes a set of temperature measurements reported in reference 3 for a stationary nitrogen cascade arc at atmospheric pressure. The measurements demonstrate that the peak (or center-line) temperature rises sharply at first with increasing average current density $\bar{j}$ and then tends to level off as it increases gradually to about 16,000° K at the largest value of $\bar{j}$ $\left(\approx 1{,}300 \text{ amp/cm}^2\right)$. The temperature profiles indicate that the tendency of the peak temperature to increase only slightly over a range of $\bar{j}$ is associated with an increase in the cross-sectional area of the hot current-carrying core through this current range. In this region the arc carries additional current by an expansion of the core rather than by an increase in conductivity.

At $\bar{j} \approx 1{,}250$ amp/cm^2 (fig. 7), the arc appears to have expanded virtually to the chamber wall so that additional current could not be carried by an increase in arc size but only through increased conductivity. Therefore, a considerable temperature increase would be expected when $\bar{j}$ is increased beyond this value. When these considerations are applied to the arc in the nozzle throat, the probable result of the sharp temperature rise would be a noticeable increase in the measured velocity. Figure 5 indicates that a rapid increase in measured peak velocity actually occurs at average current densities beyond about 1,250 amp/cm^2. The fact that the settling-chamber pressure continues to rise linearly over the range of $\bar{j}$ in which the peak velocity increases slowly is consistent with the model of an arc gradually increasing in cross-sectional area.

Effects of pressure.- According to theoretical considerations (ref. 8) the effect of increasing the pressure beyond 1 atmosphere in a stationary nitrogen arc would be a more pronounced constriction of the arc. Consequently, the temperature on the axis would increase (ref. 9), but the core would occupy a smaller cross section. For a given current, the arc will naturally assume the configuration at which the voltage gradient is a minimum. Inasmuch as the primary energy loss mechanism is conduction to the cooler gas at the arc boundary, the boundary area will naturally tend to be a minimum, subject to the constraint that the particle density in the core is sufficient to carry the current without requiring an inordinate degree of double ionization or an extreme electron drift velocity. Since the density of available particles is higher at higher pressure, the optimum core diameter is smaller.

These considerations, applied to an arc in the nozzle throat, indicate that an increasing mass flow rate should be associated with an increase in velocity as a result of the higher axial temperature. This relationship is demonstrated by the data for the long-throat nozzle (fig. 5) and to a lesser extent by the data for the intermediate-length-throat nozzle (fig. 4). Over the range of values of $\bar{J}$ for which the pressure with the arc on $\left(p = p_o \frac{p}{p_o}\right)$ exceeds 1 atmosphere, the peak velocities tend to increase somewhat with increasing mass flow rate. Further, the proclivity of the arc toward constriction with increasing pressure reduces its tendency to spread over the cross section as the current is increased, so the measured peak velocities no longer display a distinct leveling-off region.

Since the more constricted arc occupies a smaller cross-sectional area, a greater part of the mass flow is carried through the cooler and more dense region near the wall. Consequently, the settling-chamber pressure rise is smaller at the higher mass flow rates. In fact, figures 5(c) and 5(d) indicate that at pressures well above 1 atmosphere (with the arc on) the variation of settling-chamber pressure rise with average current density is no longer linear. The increase is more gradual at the higher pressures than at the lower pressures as a result of the increased arc constriction.

<u>Effects of changing flow medium</u>.- According to the theoretical considerations of reference 3, a pronounced arc core formation is characteristic of molecular gases as compared with monatomic gases. This property is associated with the usually sharp dip that occurs in the thermal conductivity of molecular gases in the temperature range where the gas approaches complete dissociation. Therefore, with nitrogen arcs the peak temperature is expected to level off over the range of values of $\bar{J}$ for which the core is expanding as shown in figure 7, and the velocity is expected to level off correspondingly as exemplified in figure 5(a); however, this phenomenon should not occur in argon. In order to test this hypothesis, a set of data was obtained with argon as the plasma medium. The results are shown in figure 6. There is apparently no leveling off of the velocity due to arc core spreading inasmuch as the variation of the peak velocity with increasing $\bar{J}$ is virtually linear.

The nitrogen plasma data of figure 5(b) correspond approximately in pressure and mass flow rate to the argon data of figure 6. Comparison of these two sets of measurements indicates that for each value of $\bar{J}$ the measured velocity is higher in nitrogen plasma than in argon plasma. This difference is a result of the considerably higher sound speed in nitrogen, which is at least partly dissociated in all the runs at higher temperatures. Actually, the arc temperature might be expected to be somewhat higher in argon than in nitrogen at the higher current levels because the second ionization potential of argon is higher than that of nitrogen.

CONCLUSIONS

This study of a cascade arc jet has utilized settling-chamber pressure-rise measurements together with direct velocity measurements to investigate some of the characteristics of the flow and of the constricted-arc heating mechanism. The results indicate the following conclusions:

1. For the nozzles used, the settling-chamber pressure rise and the peak velocity increased with increasing length-to-diameter ratio.

2. With nitrogen plasma at pressures not exceeding 1 atmosphere, the variation of the measured velocity with increasing average current density exhibited a sharp initial rise followed by a more gradual rise associated with a spreading of the arc cross section; a subsequent second sharp increase occurred at an average current density of approximately 1,300 amp/cm^2. The corresponding variation of the settling-chamber pressure rise was approximately linear.

3. A leveling off of the velocity over a range of average current density did not occur when argon was used for the plasma medium.

4. In nitrogen plasma the leveling off of the velocity diminished as the settling-chamber pressures were increased beyond 1 atmosphere. The variation of settling-chamber pressure rise with average current density was no longer linear; the pressure rise increased more slowly at the higher densities corresponding to higher pressures.

5. To the extent that the velocity can be related to the peak throat temperature and the settling-chamber pressure rise to the average temperature, the observed variation of these quantities with increasing throat length-to-diameter ratio is consistent with the analytical results reported by other investigators; and the effects of increasing current, of increasing pressure beyond 1 atmosphere, and of using a monatomic gas are consistent with experimental and analytical studies of stationary arcs.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 16, 1964.

REFERENCES

1. John, Richard R.; and Bade, William L.: Recent Advances in Electric Arc Plasma Generation Technology. ARS J., vol. 31, no. 1, Jan. 1961, pp. 4-17.

2. Shepard, Charles E.; Watson, Velvin R.; and Stine, Howard A.: Evaluation of a Constricted-Arc Supersonic Jet. NASA TN D-2066, 1964.

3. Maecker, H.: Fortschritte in der Bogenphysik. Ionization Phenomena in Gases, Vol. II, H. Maecker, ed., North-Holland Pub. Co. (Amsterdam), 1962, pp. 1793-1811.

4. Beasley, W. D.; Brooks, J. D.; and Barger, R. L.: Direct Velocity Measurements in Low-Density Plasma Flows. NASA TN D-1783, 1963.

5. Winovich, Warren: On the Equilibrium Sonic-Flow Method for Evaluating Electric-Arc Air-Heater Performance. NASA TN D-2132, 1964.

6. Rodriguez, Charles J.: An Experimental Investigation of the Effect of High-Pressure Tailpipe Length on the Performance of Solid-Propellant Motors for Rocket-Powered Aircraft. NACA RM L52E12a, 1952.

7. Stine, Howard A.; and Watson, Velvin R.: The Theoretical Enthalpy Distribution of Air in Steady Flow Along the Axis of a Direct-Current Electric Arc. NASA TN D-1331, 1962.

8. Suits, C. G.; and Poritsky, H.: Application of Heat Transfer Data to Arc Characteristics. Phys. Rev., Second ser., vol. 55, no. 12, June 15, 1939, pp. 1184-1191.

9. Suits, C. G.: The Temperature of High Pressure Arcs. J. Appl. Phys., vol. 10, no. 10, Oct. 1939, pp. 728-729.

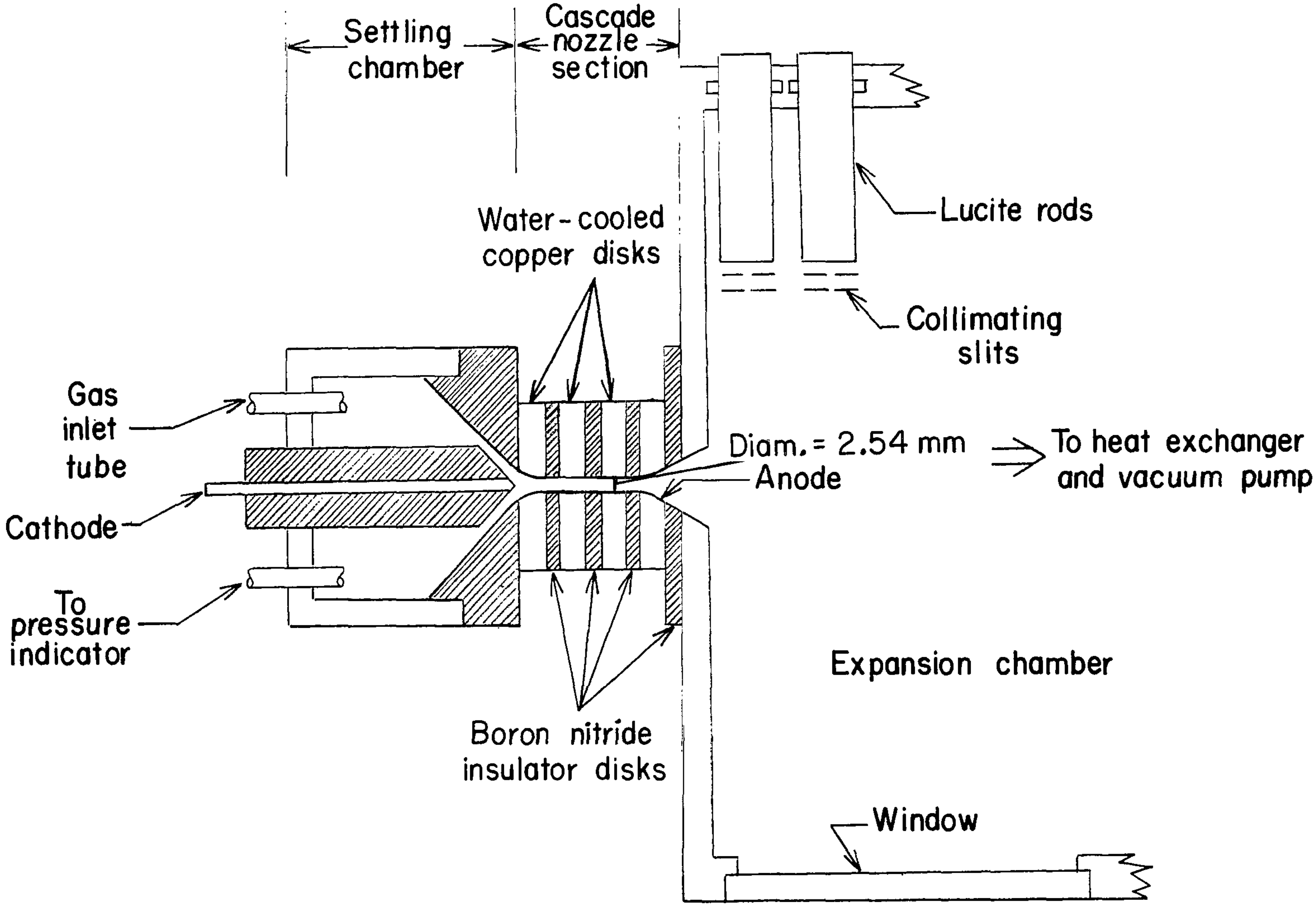


Figure 1.- Direct-current cascade arc jet and expansion chamber.

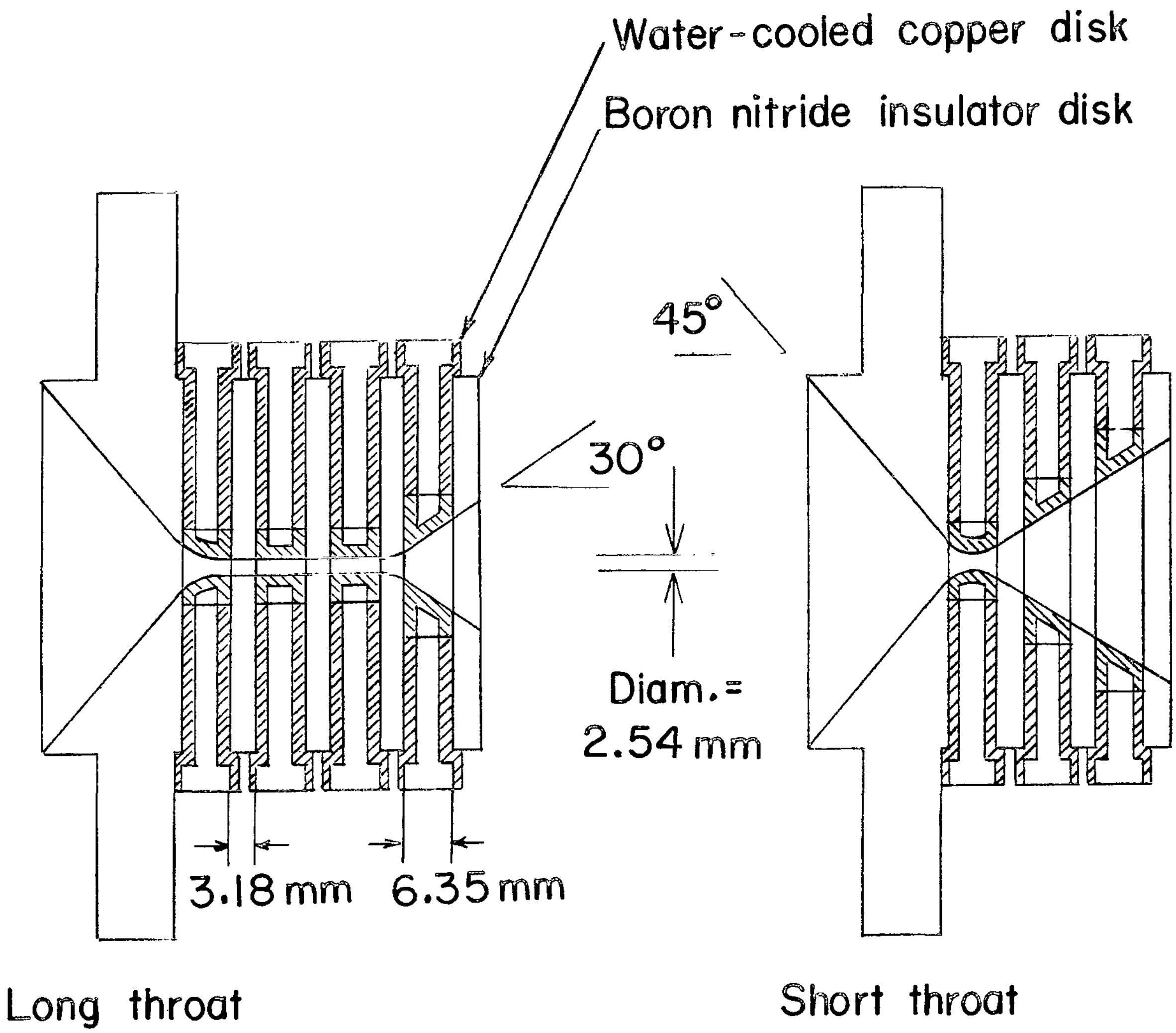


Figure 2.- Cascade-arc-jet nozzle configurations.

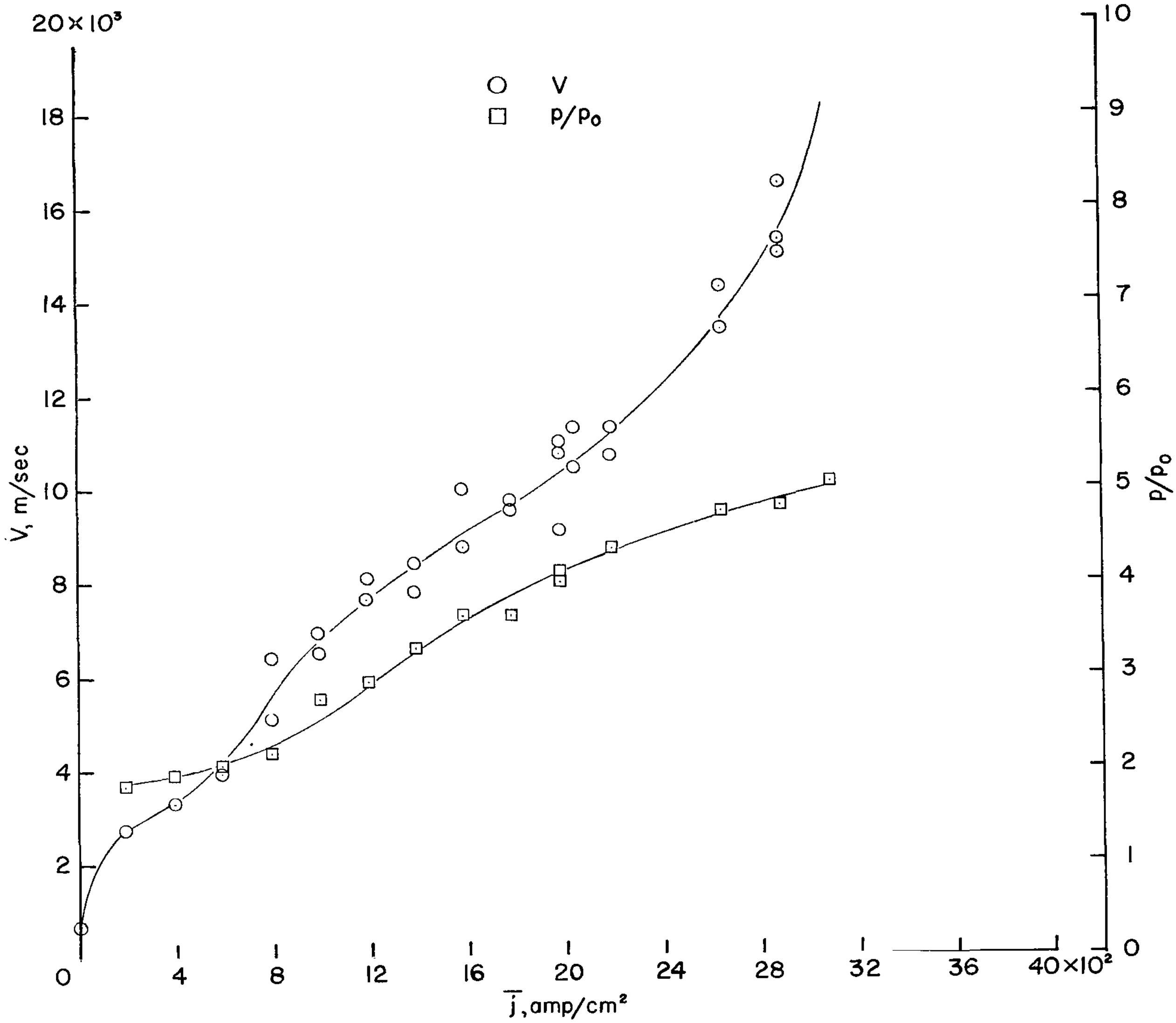
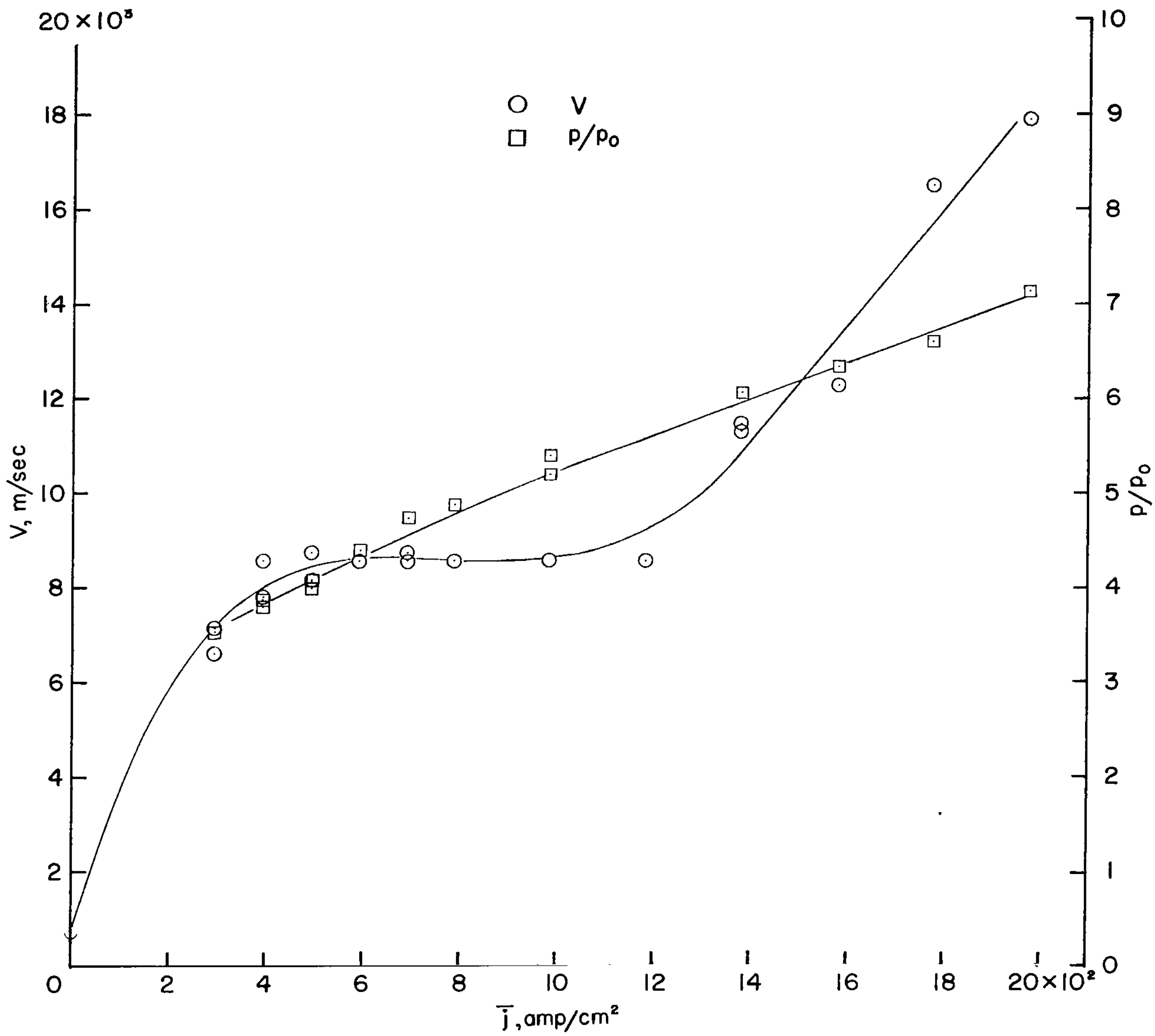
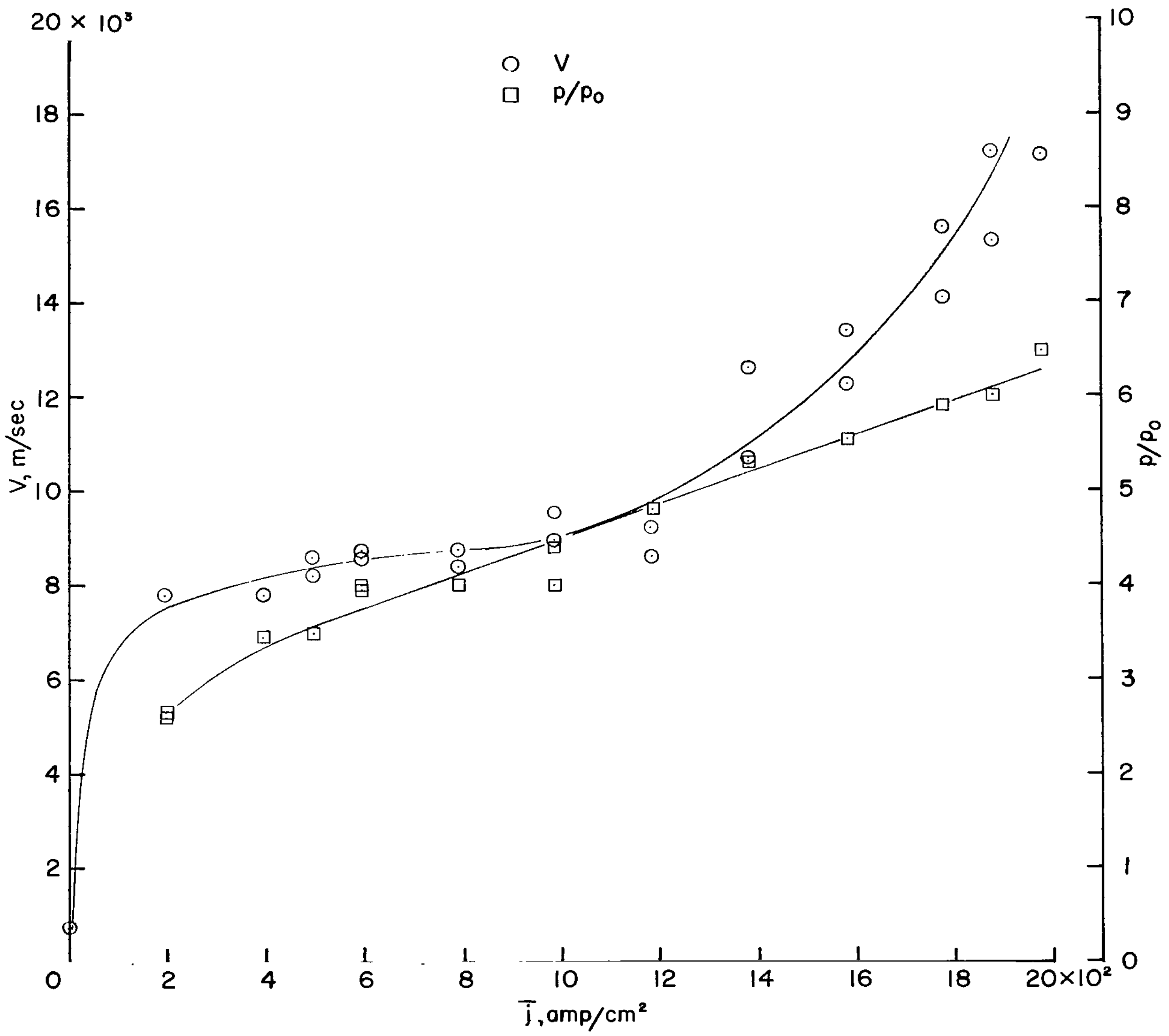


Figure 3.- Velocity and settling-chamber pressure ratio against average current density for short-throat nozzle with nitrogen plasma. $p_o \approx 85$ mm Hg; $\dot{m} = 0.101$ g/sec.



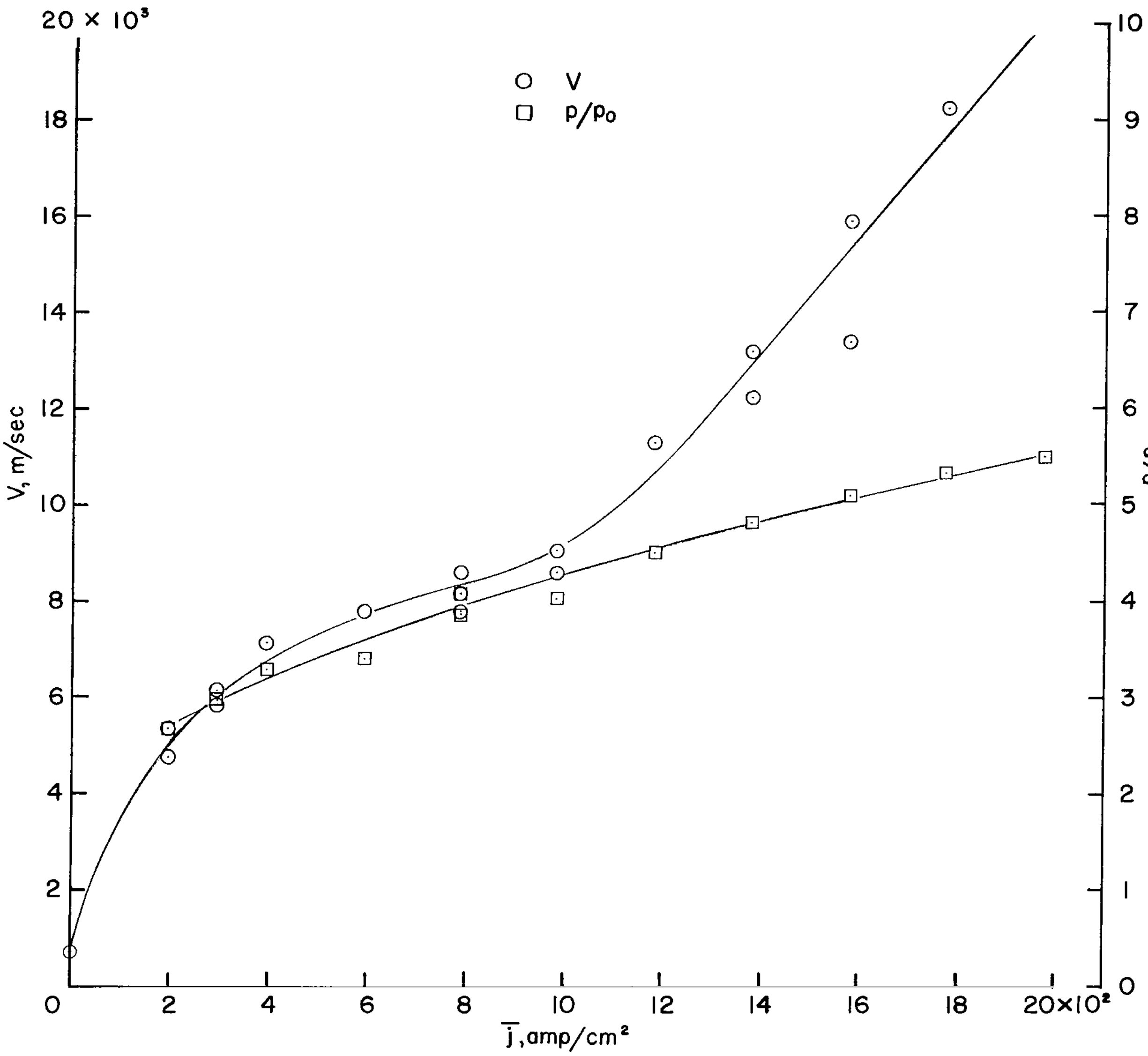
(a) $p_o \approx 75$ mm Hg; $\dot{m} = 0.077$ g/sec.

Figure 4.- Velocity and settling-chamber pressure ratio against average current density for intermediate-length-throat nozzle, $l/d = 5:1$, with nitrogen plasma.



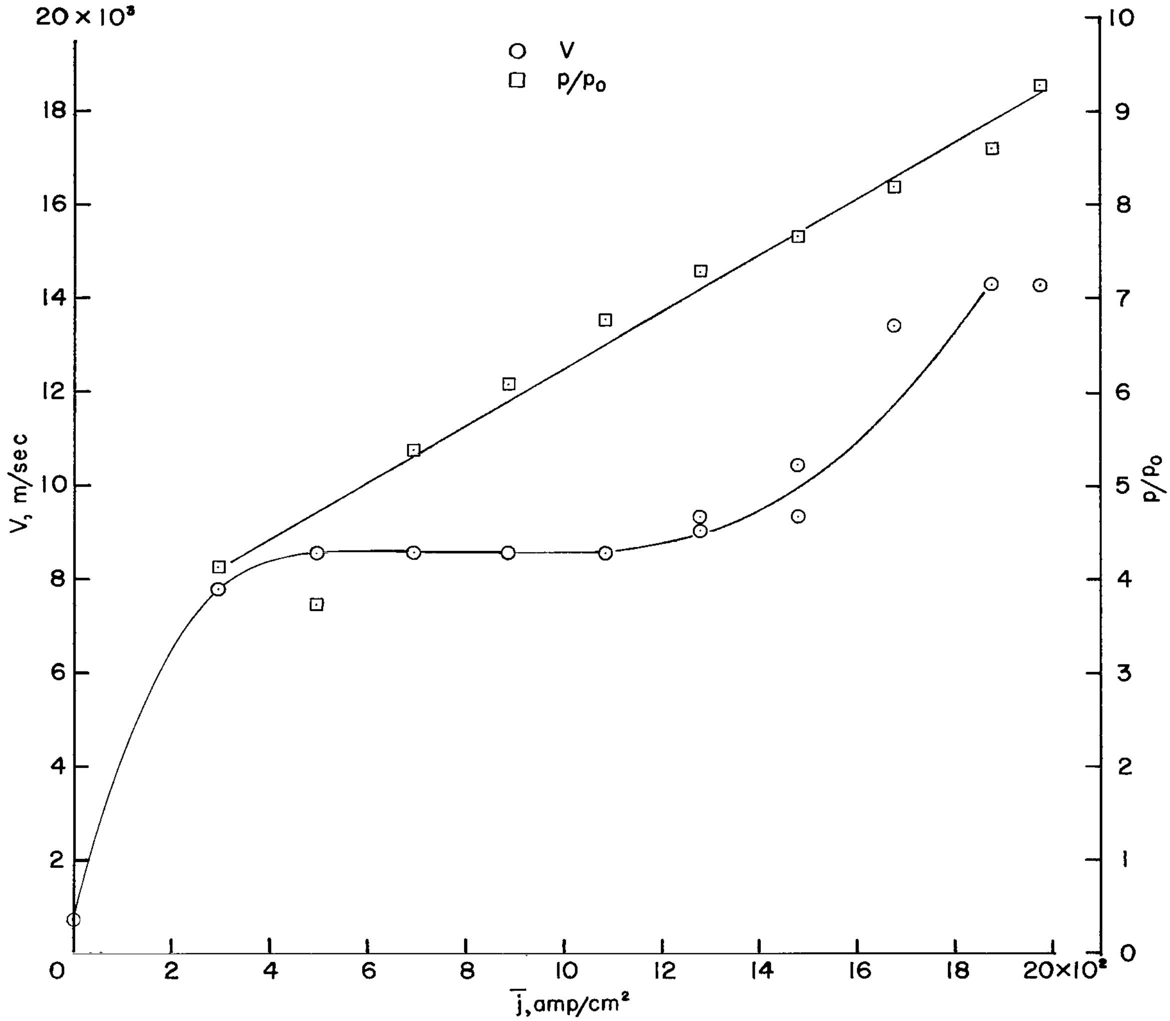
(b) $p_o \approx 100$ mm Hg; $\dot{m} = 0.106$ g/sec.

Figure 4.- Continued.



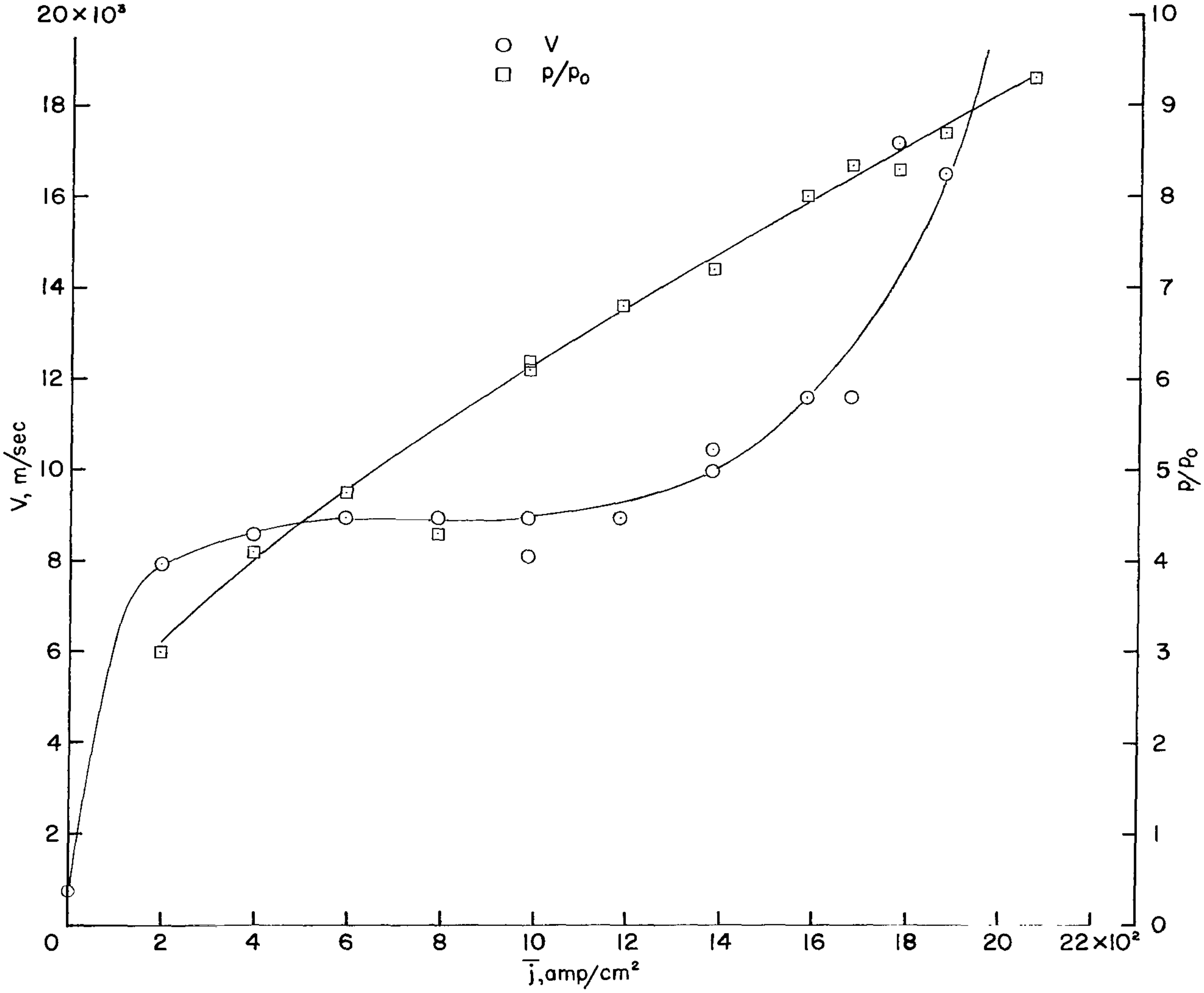
(c) $p_o \approx 150$ mm Hg; $\dot{m} = 0.151$ g/sec.

Figure 4.- Concluded.



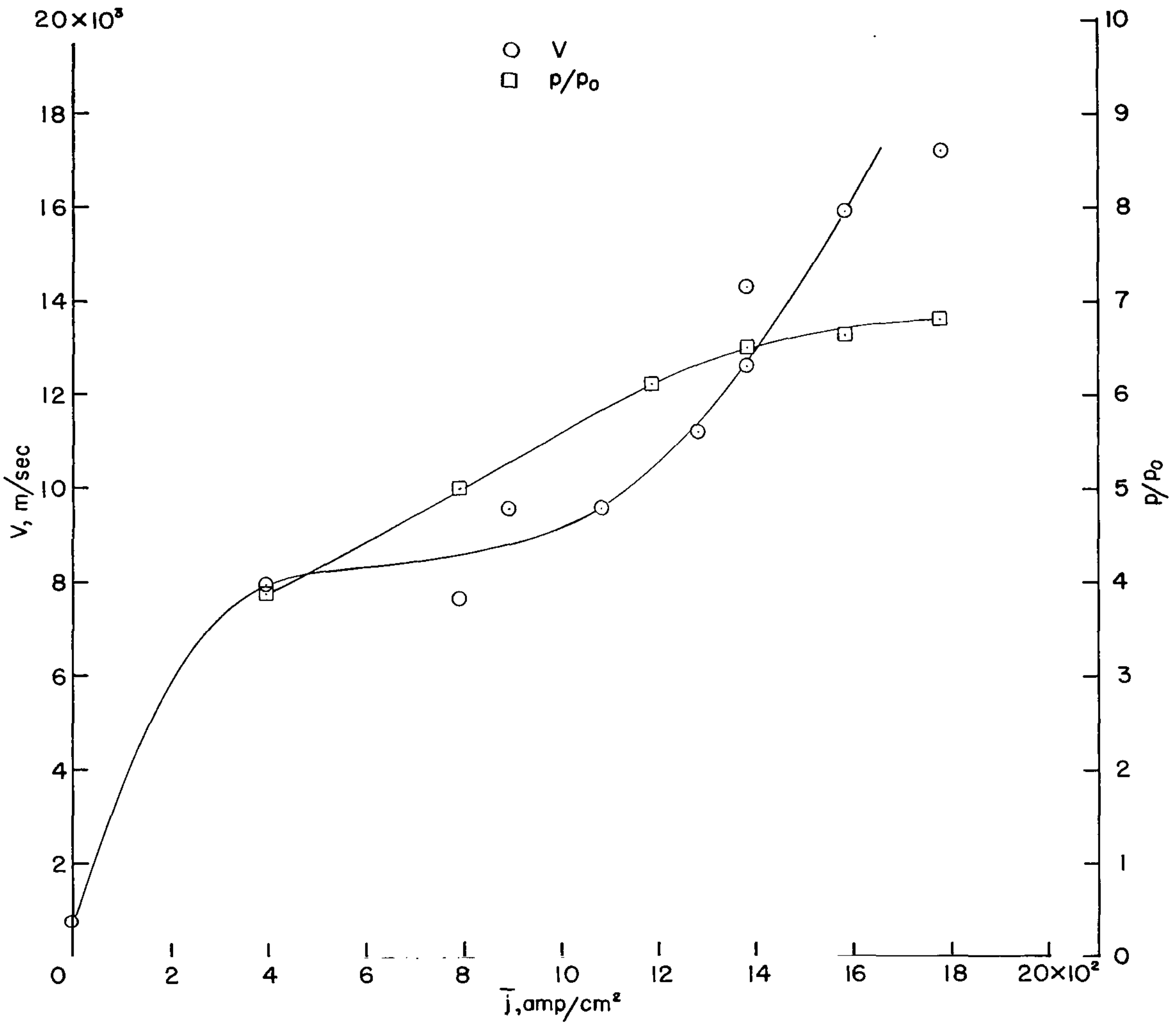
(a) $p_o \approx 75$ mm Hg; $\dot{m} = 0.073$ g/sec.

Figure 5.- Velocity and settling-chamber pressure ratio against average current density for long-throat nozzle, $l/d = 9:1$, with nitrogen plasma.



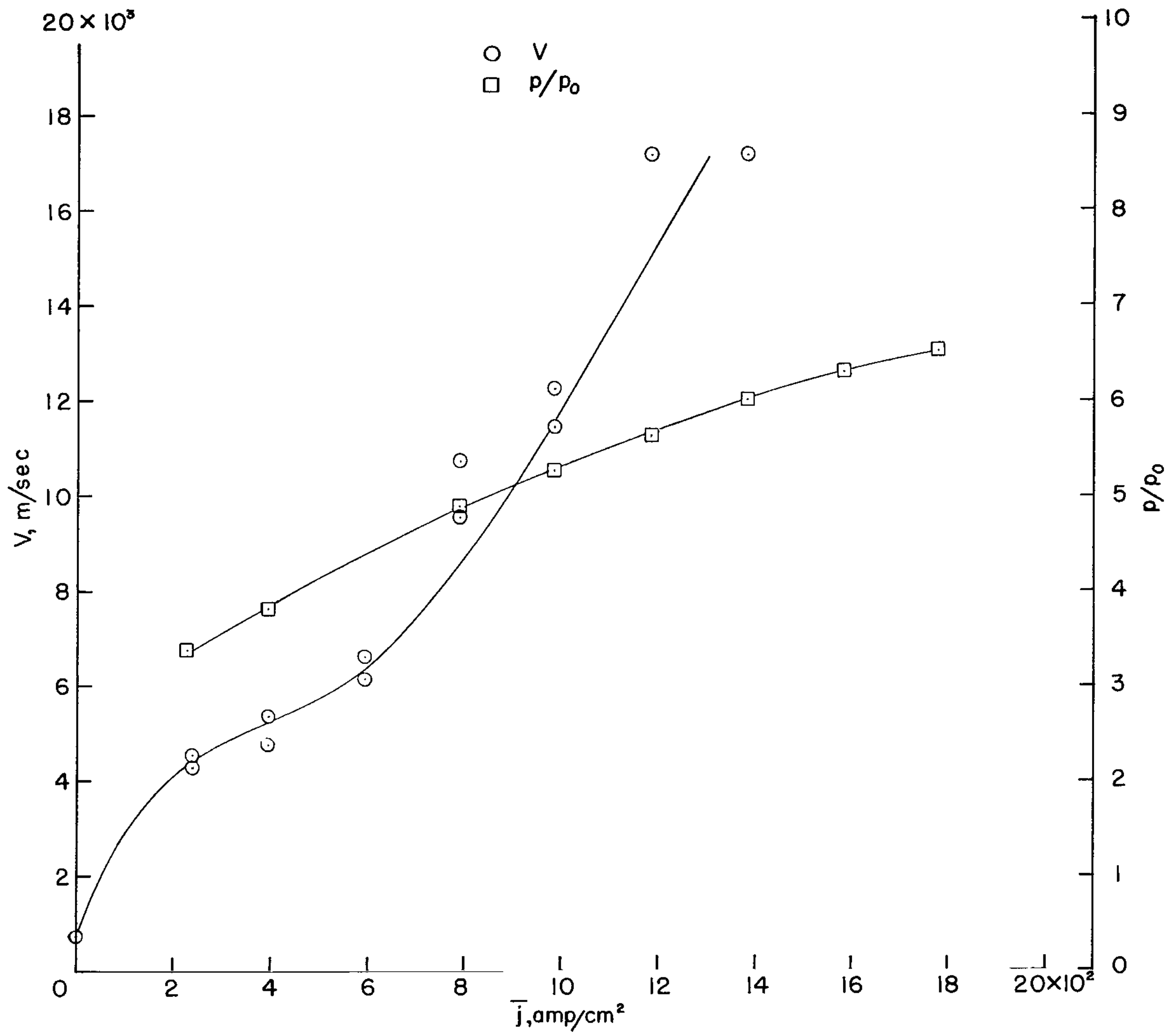
(b) $p_o \approx 100$ mm Hg; $\dot{m} = 0.102$ g/sec.

Figure 5.- Continued.



(c) $p_o \approx 150$ mm Hg; $\dot{m} = 0.160$ g/sec.

Figure 5.- Continued.



(d) $p_o \approx 215$ mm Hg; $\dot{m} = 0.300$ g/sec.

Figure 5.- Concluded.

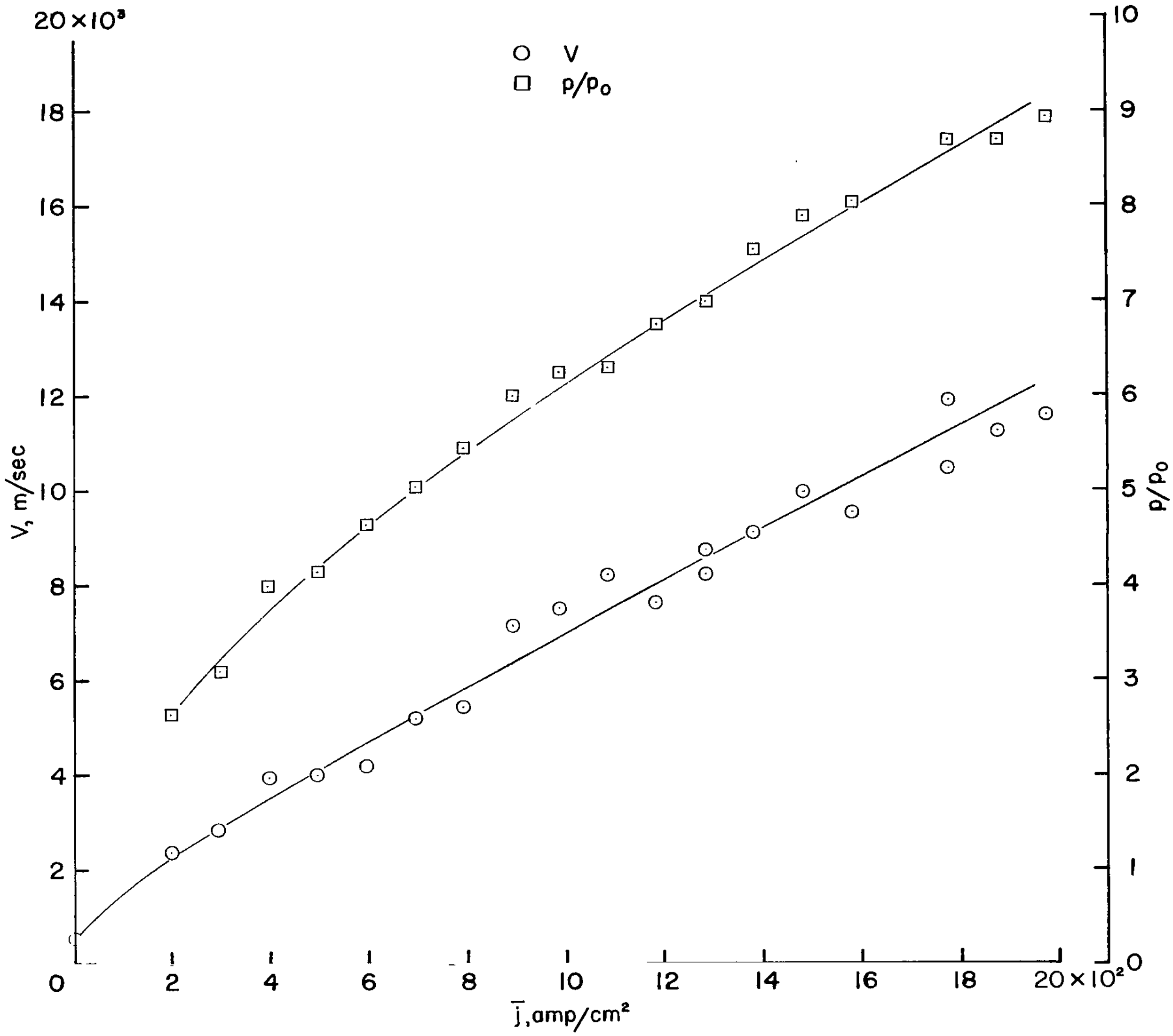


Figure 6.- Velocity and settling-chamber pressure ratio against average current density for long-throat nozzle, $l/d = 9:1$, with argon plasma. $p_o \approx 100$ mm Hg; $\dot{m} = 0.124$ g/sec.

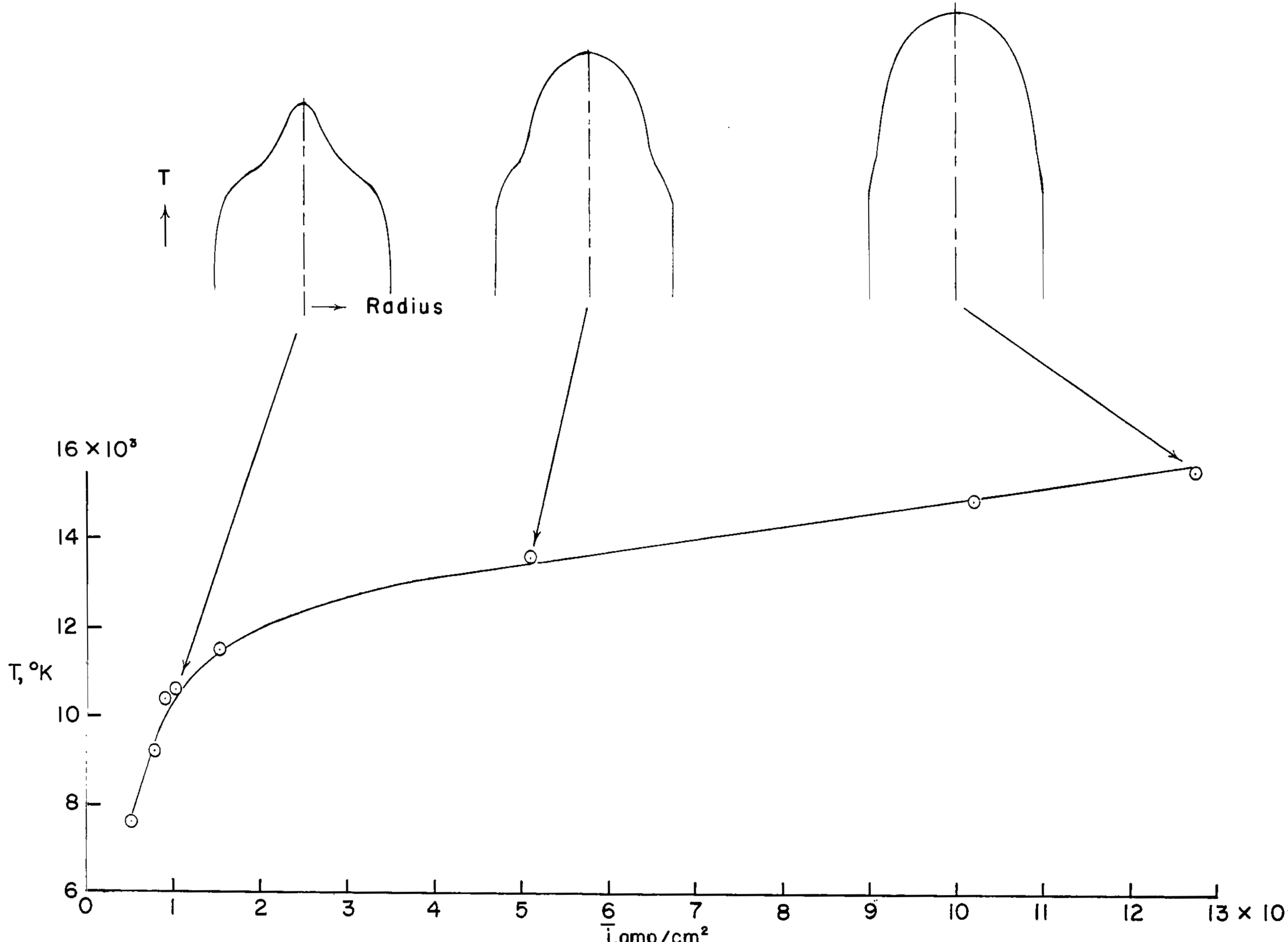


Figure 7.- Peak temperatures and temperature profiles of a nitrogen arc at atmospheric pressure (from ref. 3).

2/22/85

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546